Simulating New Physics at LHC

Bryan Webber

Sussex seminar, 29 April 2001

- Large Hadron Collider
- HERWIG Event Generator
  - Event structure
  - Parton showers & hadronization model
  - Spin correlations
- New Physics Studies
  - Distinguishing SUSY models
  - Graviton excitations
  - Black hole production
- Future Plans
- Conclusions

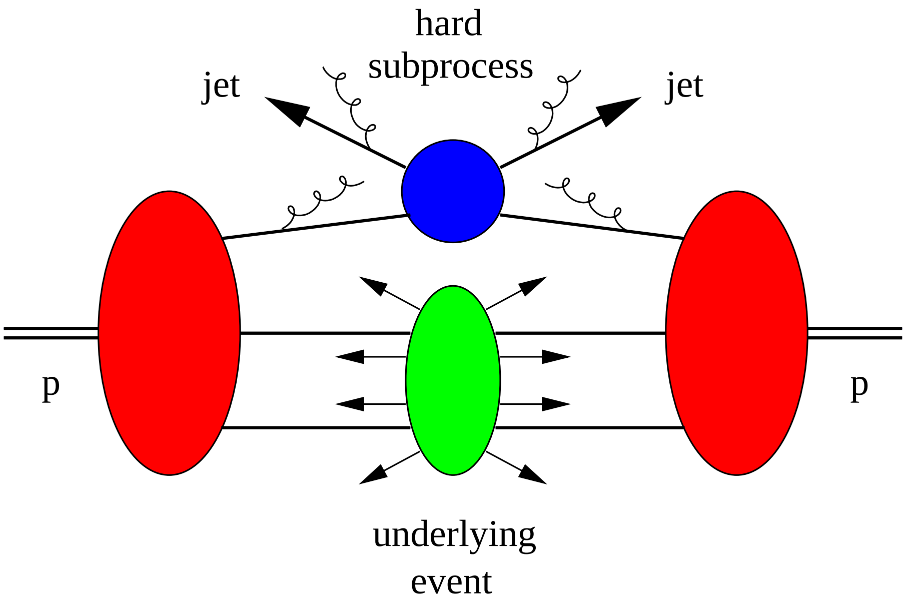
HERWIG 5.1: G Marchesini, BRW, G Abbiendi, IG Knowles, MH Seymour, L Stanco & BRW, CPC 67(1992)465
HERWIG 6.1: G Corcella, IG Knowles, G Marchesini, S Moretti, K Odagiri, P Richardson, MH Seymour & BRW, JHEP 0101(2001)010
Cambs SUSY Working Group: http://www.hep.phy.cam.ac.uk/atlas/susy/

The Large Hadron Collider

- The largest machine ever built
  - 7 TeV proton beams in existing (LEP) tunnel
  - Total beam energy = 200 ton train at 200 km/hr
  - Beam spot size 30 μm
  - 1158 superconducting 15 metre 8.4 Tesla magnets
  - 700,000 litres liquid helium
  - First collisions $\rightarrow$ 2007
  - Luminosity 10^{34} cm^{-2}s^{-1}
    - $\sigma = 1$ fb $\Rightarrow$ 100 events/yr

- What to do meanwhile?
  - Given any theory, what should happen at LHC?
  - Full event simulations, both SM and BeyondSM
  - Use these to refine theory, detectors and analysis

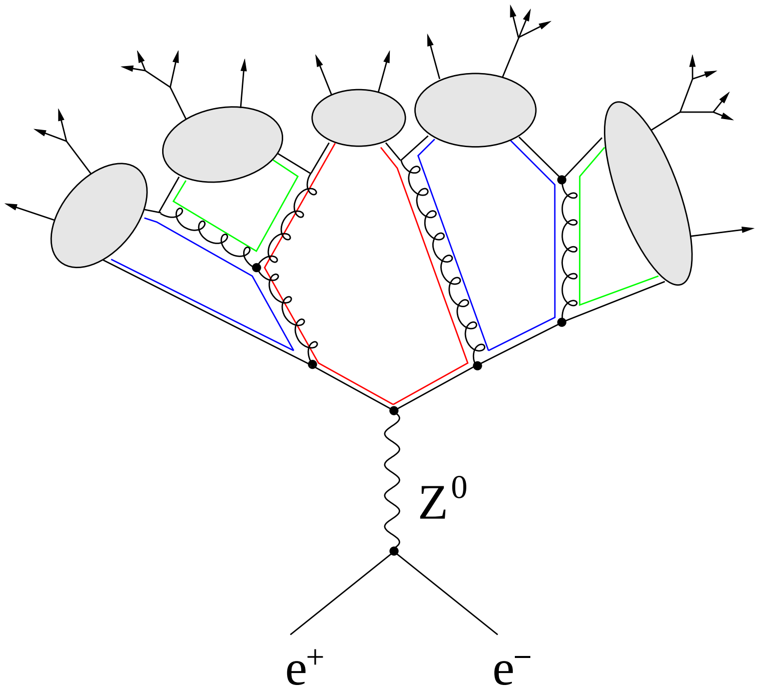
LHC Event Simulation



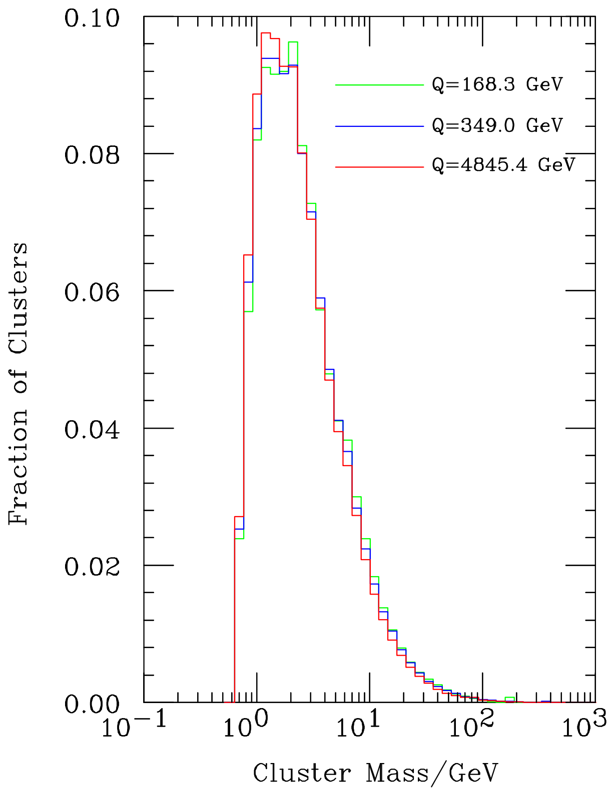
- Each collision event has several components:
  - Constituent distributions: quarks, antiquarks, gluons
  - Hard subprocess: collision between constituents
  - Quark/gluon showering on incoming/outgoing constituents
  - Underlying event due to proton remnants
  - Hadronization: confinement of quarks and gluons.
- Hard subprocess is where new BSM physics should occur.

HERWIG Event Generator

- Parton showers and cluster hadronization model



- Cluster mass spectrum is universal



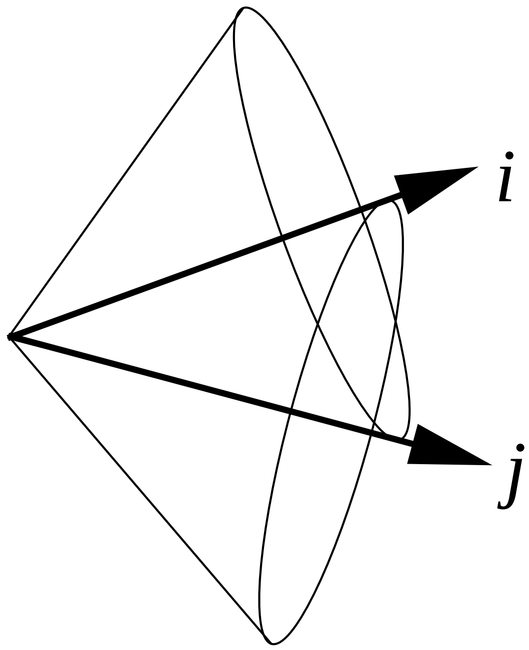
- HERWIG's adjustable parameters:

Parameter	Affects	Default	OPAL
QCDLAM	$\Lambda \sim \Lambda^{(5)}_{\overline{\mathrm{MS}}}$	0.180	D
RMASS(13)	cutoff "m_g"	0.750	D
CLMAX	cluster mass limit	3.35	D
CLPOW	cluster splitting	2.0	D
PSPLT(1)	cluster spectrum (udsc)	1.0	D
PSPLT(2)	cluster spectrum (b)	1.0	0.33
CLSMR(1)	cluster decay (udsc)	0.0	0.40
CLSMR(2)	cluster decay (b)	0.0	D
PWT(3)	s quark weight	1.0	–
PWT(7)	diquark weight	1.0	–
SNGWT	baryon weight (1)	1.0	–
DECWT	baryon weight (10)	1.0	0.7

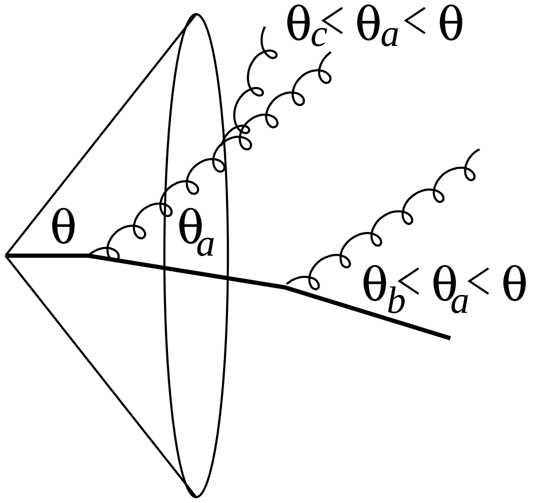
For details see http://home.cern.ch/webber/hwtune.html

- LEP and Tevatron data are reproduced well overall, with some discrepancies near kinematic boundaries. Baryon and heavy flavour yields are less well described.

- Colour coherence is simulated by angular ordering:
  - Angular region for shower from parton i is cone bounded by direction of j (and vice-versa), where i and j are colour-connected:



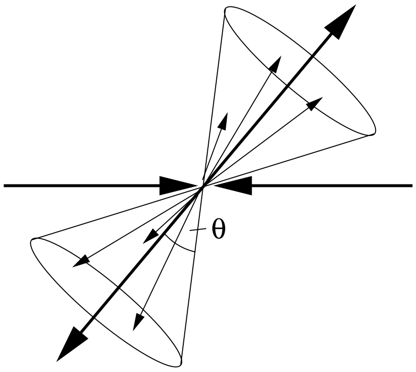
  - Angles within shower decrease away from hard subprocess:



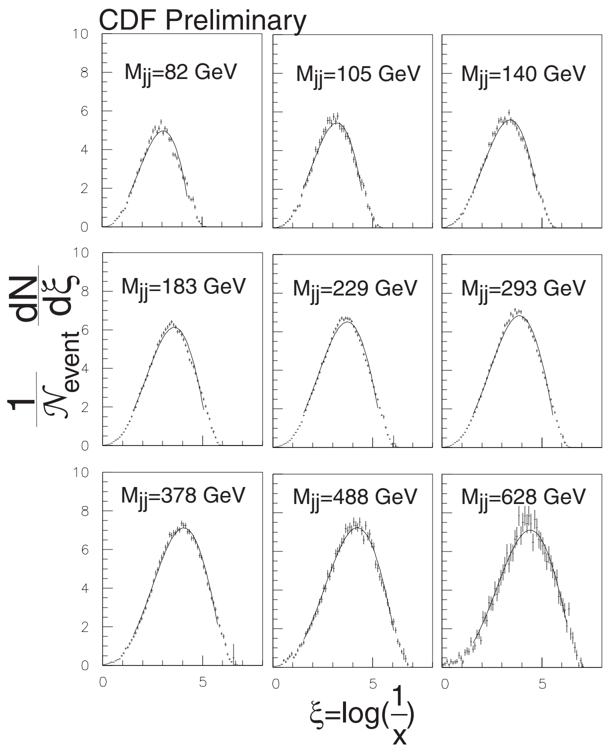
  - This suppresses soft gluon/hadron production

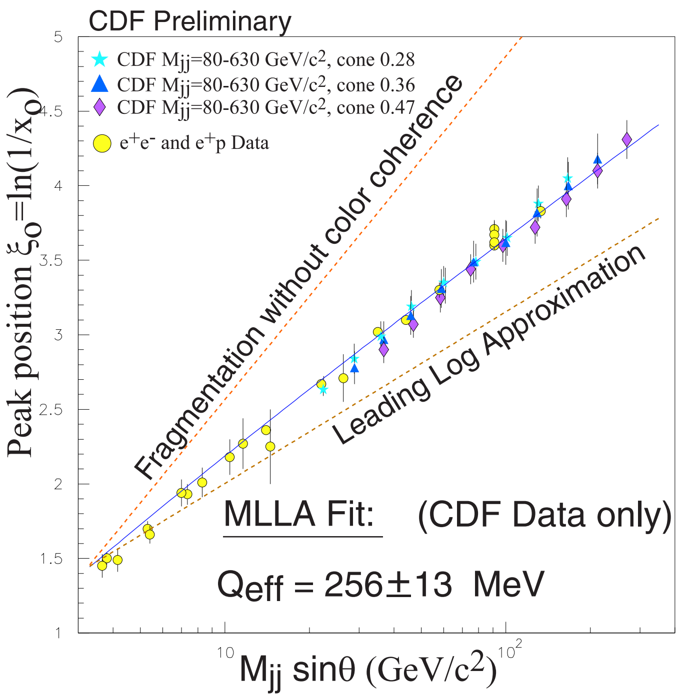
- Beautifully confirmed by Tevatron dijet data

CDF Collaboration



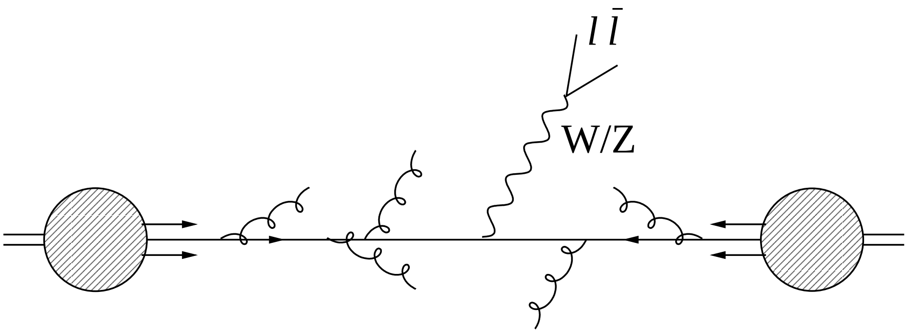
$x = p_{had}/E_{jet}$



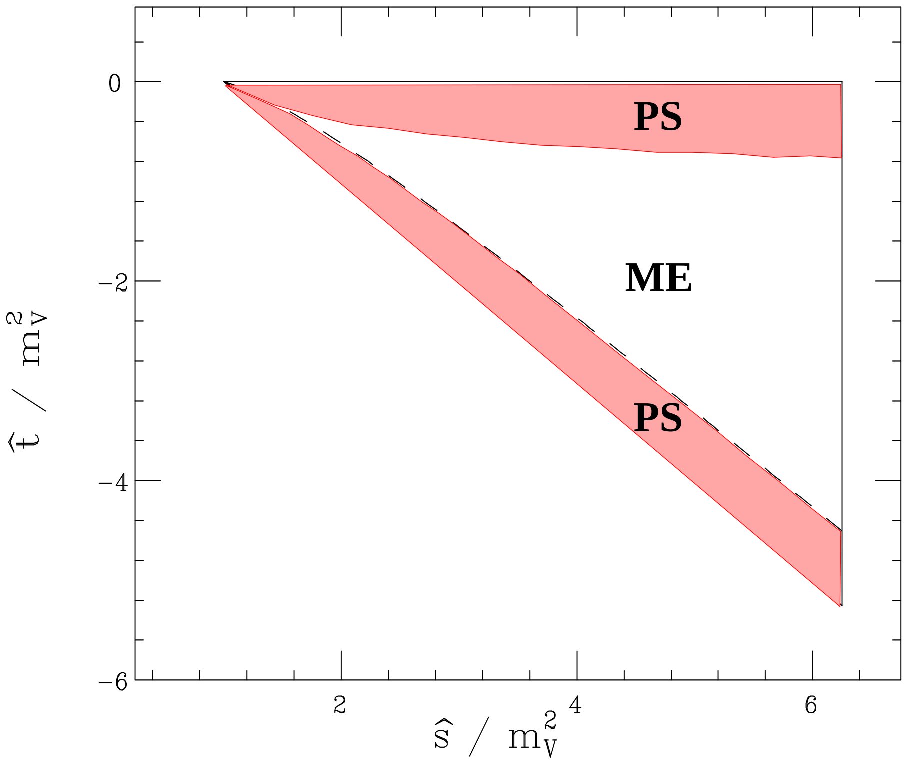


- Parton showers inside cones do not populate whole phase space. We also have to include (less singular) matrix element corrections

- For example, in W/Z hadroproduction

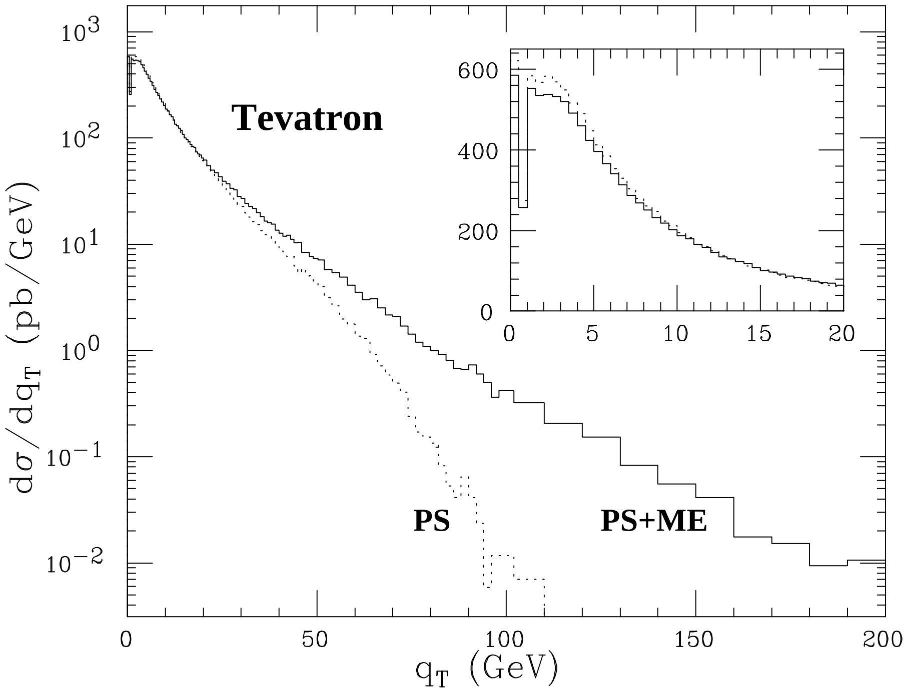


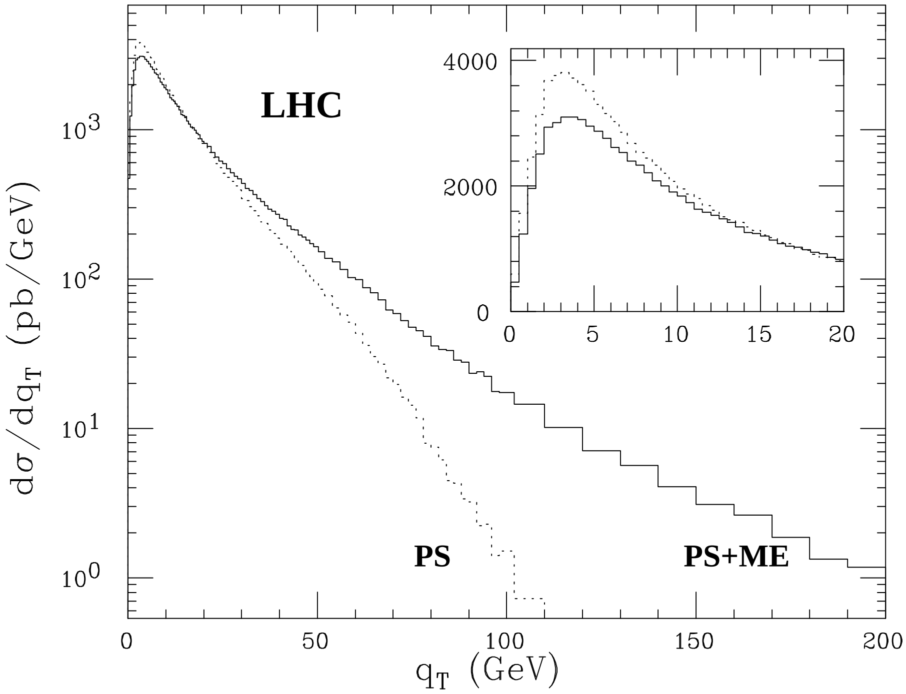
- Phase space for W + jet



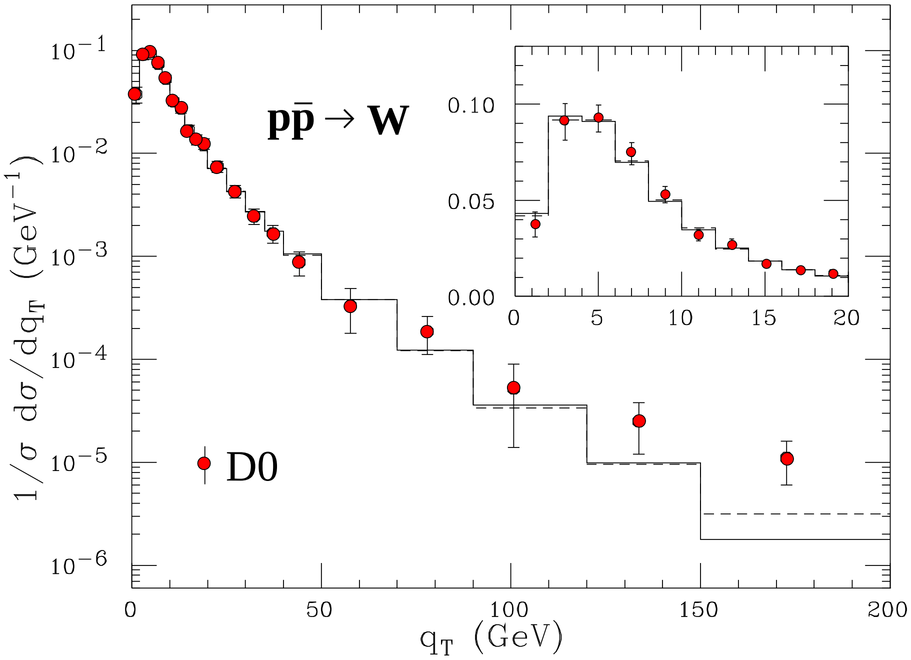
- ME corrections essential for W/Z production at large transverse momentum (important background to new physics):

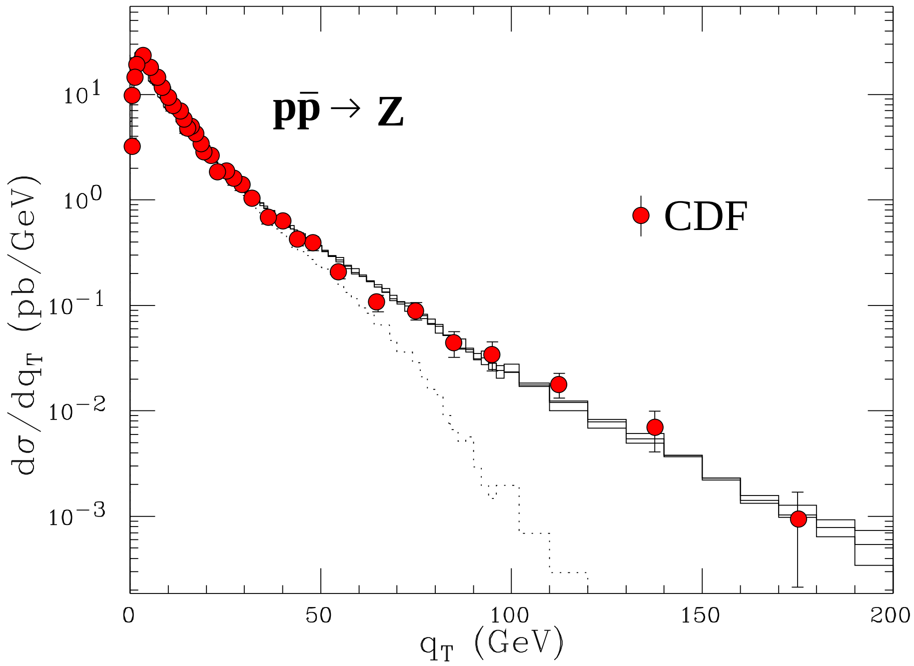
G Corcella & MH Seymour, Nucl Phys B565(2000)227





Comparisons with Tevatron data:





Spin Correlations

JC Collins, NP B304(1988)794

IG Knowles, NP B304(1988)767, B310(1988)571; CPC 58(1990)271

P Richardson, JHEP 0111(2001)029

- Completely general way of implementing all spin correlations

- Previous approaches required production and decay of particles to be generated at same time. Difficult if:
  - There is QCD radiation from particles before they decay
  - Particles have many decay modes
  - There are many sequential decays
  - There are many final state particles

- For Monte Carlo event generation we need an algorithm in which:
  - Production and decay can be generated separately
  - Complexity grows only linearly with number of particles

- Consider e.g. $ab \to cd$ with decays of c and d. Using factorization of the matrix element we can write

$$|\mathcal{M}_{\rm total}|^2 = \rho^{\lambda_c\lambda'_c\lambda_d\lambda'_d} D_c^{\lambda_c\lambda'_c} D_d^{\lambda_d\lambda'_d}$$

where

$$\rho_{\rm prod}^{\lambda_c\lambda'_c\lambda_d\lambda'_d} = \mathcal{M}_{ab\to cd}^{\lambda_c\lambda_d}\mathcal{M}_{ab\to cd}^{*\lambda'_c\lambda'_d}$$

is the unnormalized spin density matrix and

$$D_c^{\lambda_c \lambda'_c} = \mathcal{M}_{c\ \text{decay}}^{\lambda_c} \mathcal{M}_{c\ \text{decay}}^{*\lambda'_c}$$

the unnormalized decay matrix.

- Consider for definiteness $e^+e^- \to t\bar{t}$ with semi-leptonic decay of top quarks. First generate momenta of top quarks using polarized differential cross-section

$$\rho^1_{\kappa_1\kappa'_1}\rho^2_{\kappa_2\kappa'_2}\mathcal{M}_{\kappa_1\kappa_2;\lambda_1\ldots\lambda_n}\mathcal{M}^*_{\kappa'_1\kappa'_2;\lambda_1\ldots\lambda_n}$$

- One of outgoing quarks is selected at random and a spin density matrix calculated

$$\begin{aligned}\rho_{\lambda_j\lambda'_j} &= \frac{1}{N_\rho}\rho^1_{\kappa_1\kappa'_1}\rho^2_{\kappa_2\kappa'_2}\prod_{i\neq j} D^i_{\lambda_i\lambda'_i} \\ &\quad \mathcal{M}_{\kappa_1\kappa_2;\lambda_1\ldots\lambda_j\ldots\lambda_n}\mathcal{M}^*_{\kappa'_1\kappa'_2;\lambda'_1\ldots\lambda'_j\ldots\lambda'_n}\end{aligned}$$

- In initial step we take $D^i_{\lambda_i\lambda'_i} = \delta_{\lambda_i\lambda'_i}$. Normalization N_ρ is chosen so that $\mathrm{Tr}\rho = 1$. This cancels matrix element used in previous step.

- Decay mode of the particle is selected using the branching ratios. Momenta of the particles produced in n-body decay are generated using

$$\rho_{\lambda_0\lambda'_0}\mathcal{M}_{\lambda_0;\lambda_1\ldots\lambda_n}\mathcal{M}^*_{\lambda'_0;\lambda_1\ldots\lambda_n}$$

- When all the particles in a decay have been developed a decay matrix is calculated

$$D_{\lambda_0\lambda'_0} = \frac{1}{N_D}\mathcal{M}_{\lambda_0;\lambda_1\ldots\lambda_n}\mathcal{M}^*_{\lambda'_0;\lambda'_1\ldots\lambda'_n}\prod_{i=1,n} D^i_{\lambda_i\lambda'_i}$$

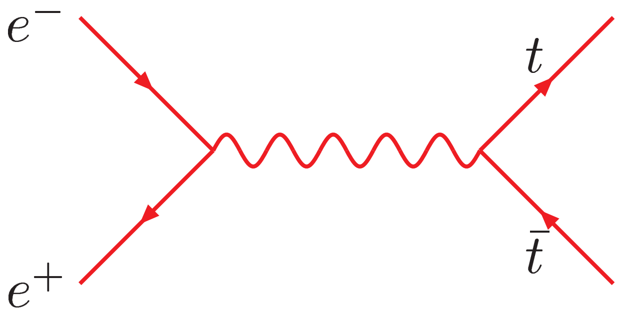
Normalization N_D is chosen so that $\mathrm{Tr}D = 1$.

- Then select another particle from the hard process. The whole procedure is repeated for this particle using the calculated decay matrices for those particles which have been decayed, rather than the identity.

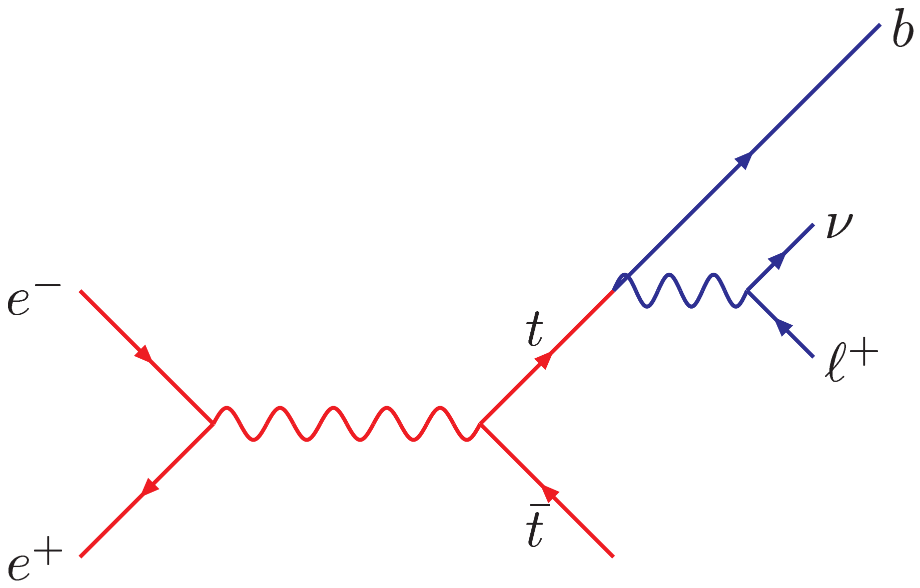
- In this case this means we decay the second quark.

- As before the normalization of the spin density matrix cancels the matrix element used for the previous step.

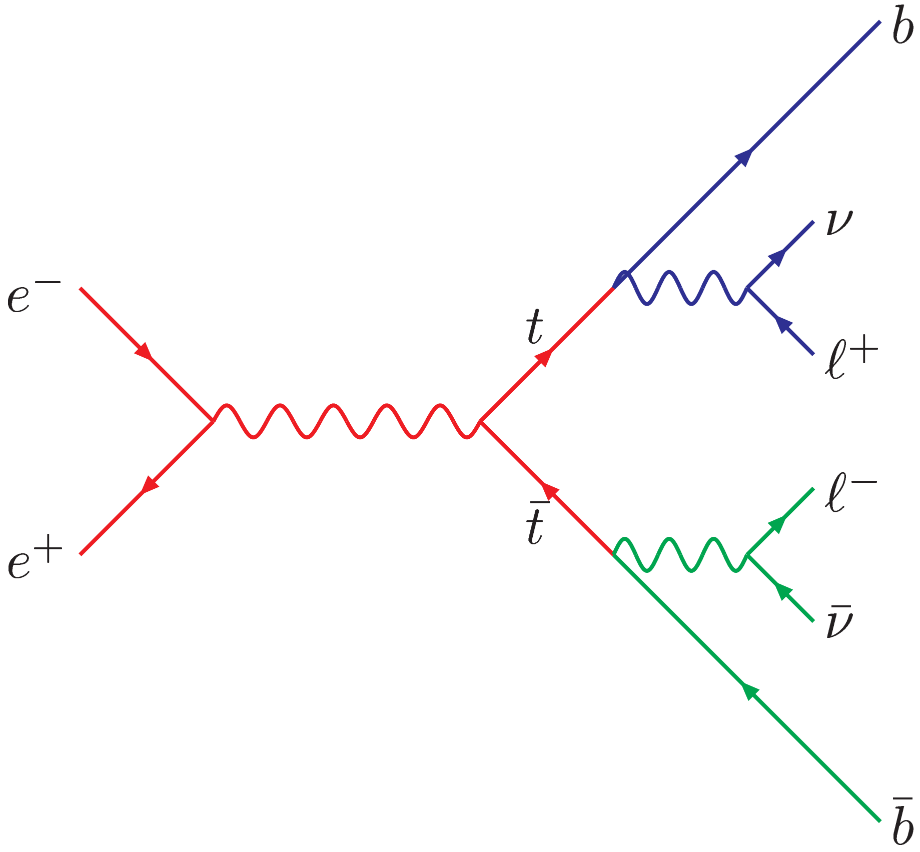
Top Pair Production



$$|\mathcal{M}|^2 = \rho^1_{\kappa_1\kappa'_1}\rho^2_{\kappa_2\kappa'_2}\mathcal{M}^{e^+e^-\to t\bar{t}}_{\kappa_1\kappa_2;\lambda_t\lambda_{\bar{t}}}\mathcal{M}^{*e^+e^-\to t\bar{t}}_{\kappa'_1\kappa'_2;\lambda_t\lambda_{\bar{t}}}$$



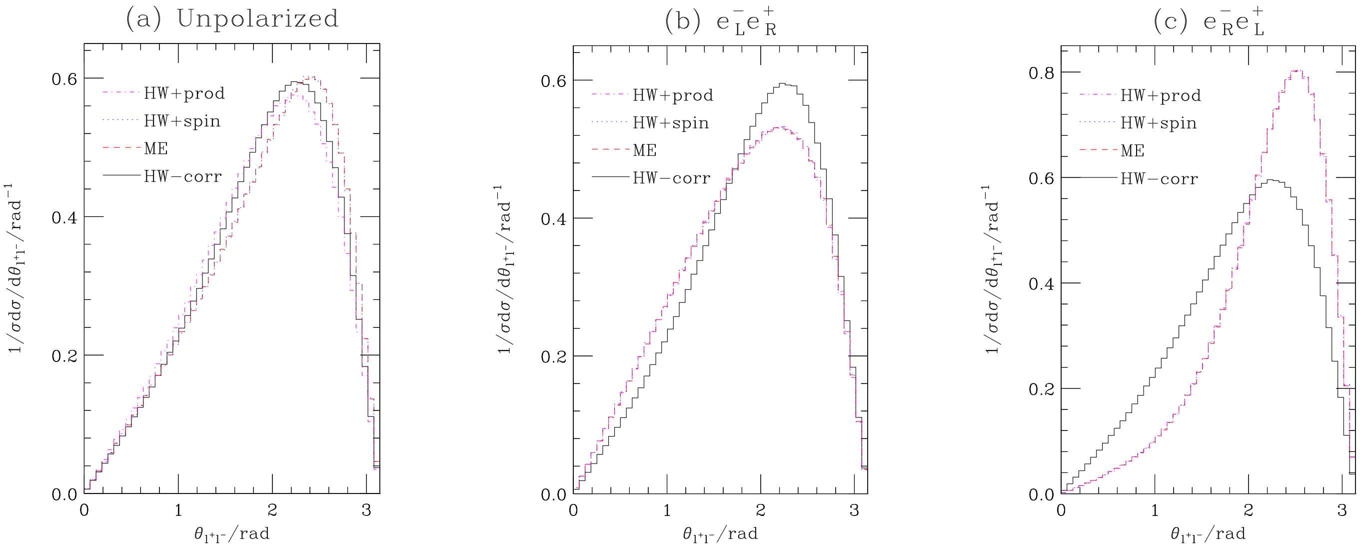
$$|\mathcal{M}|^2 = \rho^1_{\kappa_1\kappa'_1}\rho^2_{\kappa_2\kappa'_2}\mathcal{M}^{e^+e^-\to t\bar{t}}_{\kappa_1\kappa_2;\lambda_t\lambda_{\bar{t}}}\mathcal{M}^{*e^+e^-\to t\bar{t}}_{\kappa'_1\kappa'_2;\lambda'_t\lambda_{\bar{t}}} \mathcal{M}^{t\to b\ell\nu}_{\lambda_t}\mathcal{M}^{*t\to b\ell\nu}_{\lambda'_t}$$



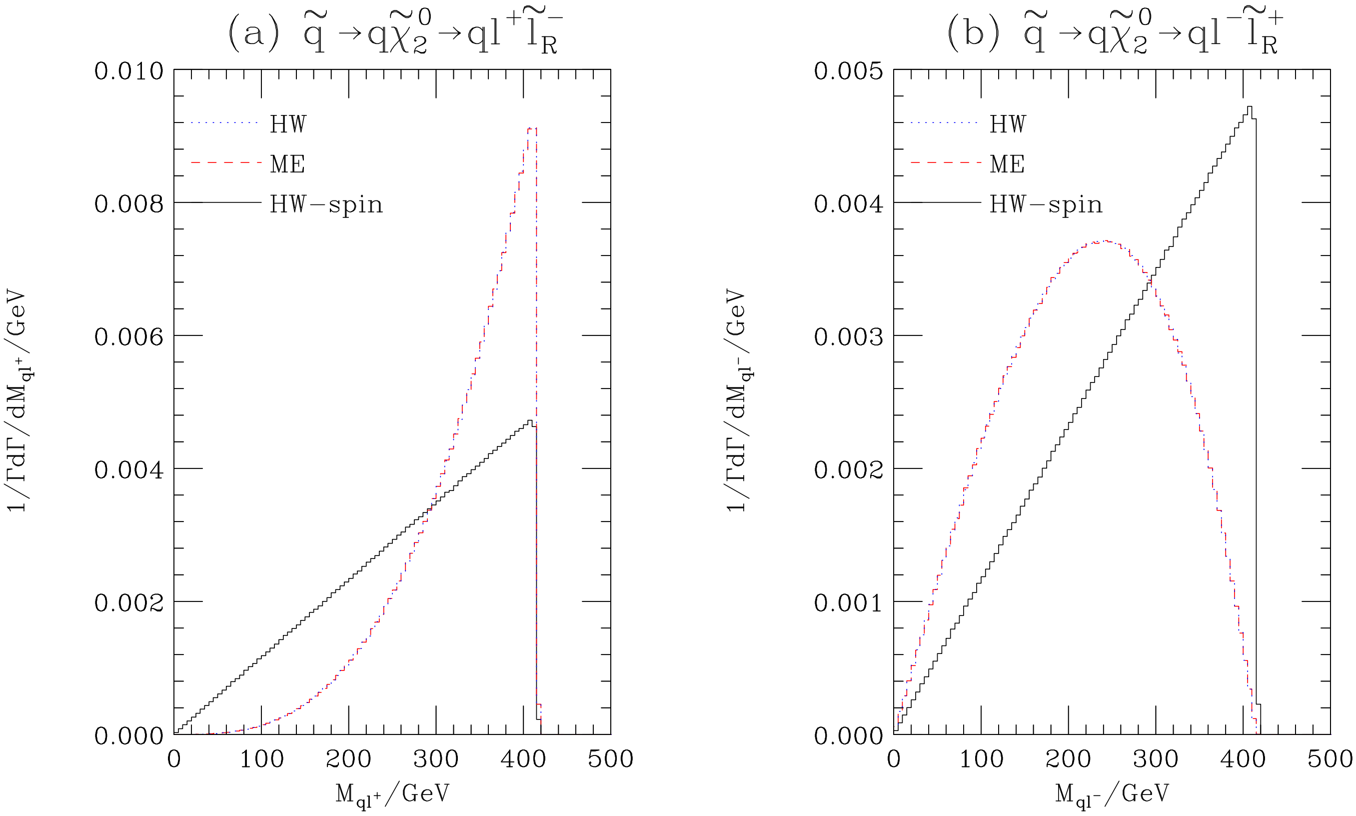
$$
\begin{aligned}
|\mathcal{M}|^2 \quad = \quad & \rho^1_{\kappa_1\kappa'_1}\rho^2_{\kappa_2\kappa'_2}\mathcal{M}^{e^+e^-\to t\bar{t}}_{\kappa_1\kappa_2;\lambda_t\lambda_{\bar{t}}}\mathcal{M}^{*e^+e^-\to t\bar{t}}_{\kappa'_1\kappa'_2;\lambda'_t\lambda'_{\bar{t}}} \\
& \mathcal{M}^{t\to b\ell\nu}_{\lambda_t}\mathcal{M}^{*t\to b\ell\nu}_{\lambda'_t} \\
& \mathcal{M}^{\bar{t}\to\bar{b}\ell\nu}_{\lambda_{\bar{t}}}\mathcal{M}^{*\bar{t}\to\bar{b}\ell\nu}_{\lambda'_{\bar{t}}}
\end{aligned}
$$

- This procedure gives the full matrix element, but allows us to generate the event step by step

- Final lepton-antilepton angular correlation:



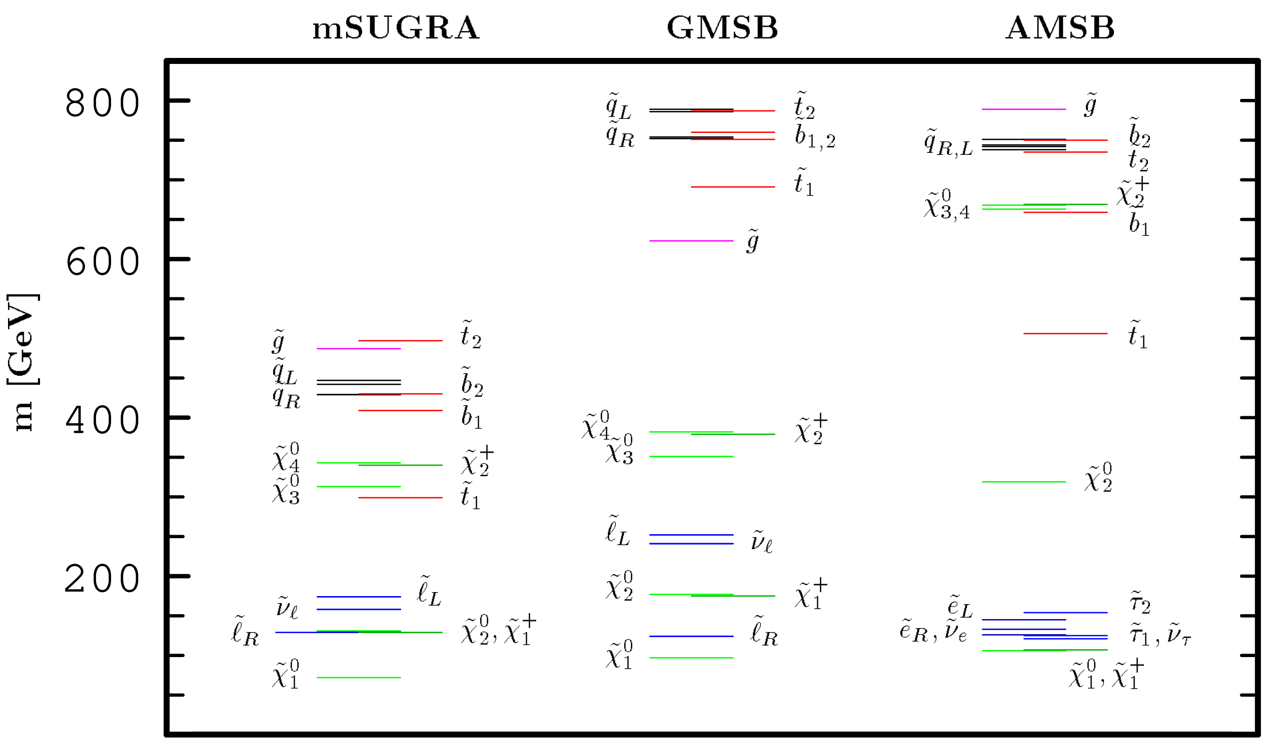
- Effects can also be important in sequential SUSY decays:



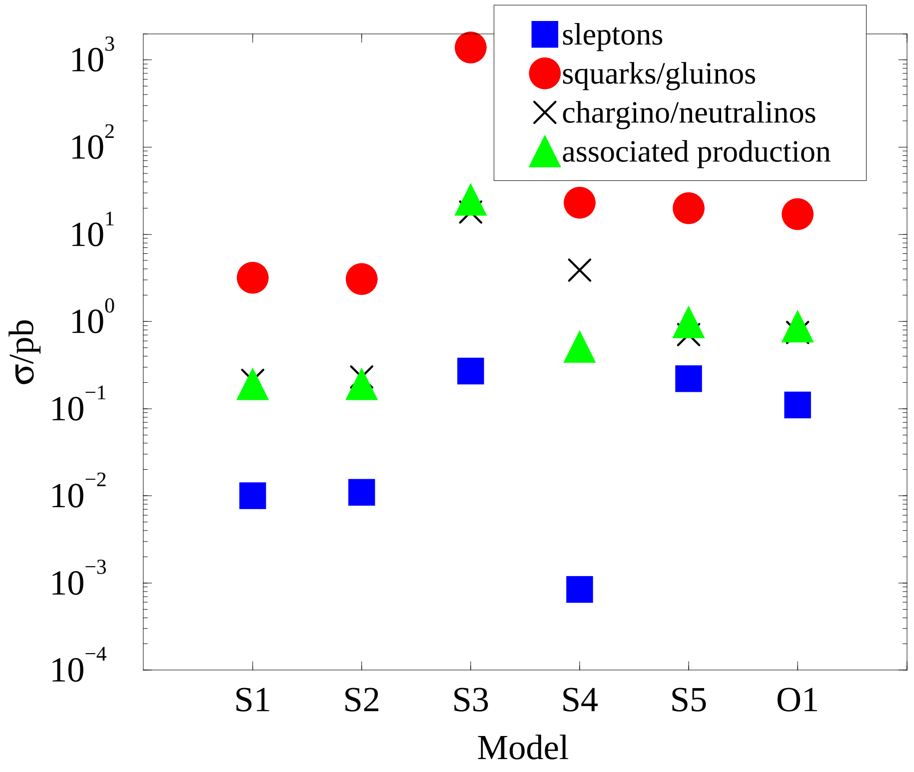
Distinguishing between SUSY models

BC Allanach, CG Lester, MA Parker & BRW, hep-ph/0007009

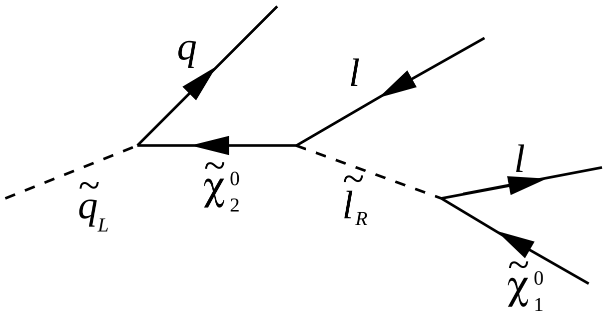
- SUSY needs 2 Higgs doublets $\Rightarrow$ extra Higgs bosons
- Higgsinos mix with electroweak gauginos $\Rightarrow$ neutralinos $\tilde{\chi}^0_{1,2,3,4}$ and charginos $\tilde{\chi}^{\pm}_{1,2}$
- Lightest neutralino $\tilde{\chi}^0_1$ is often stable LSP
- Further details depend on model for SUSY breaking

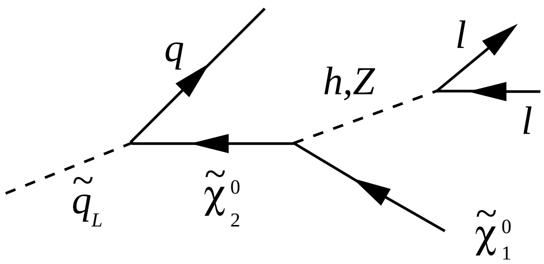


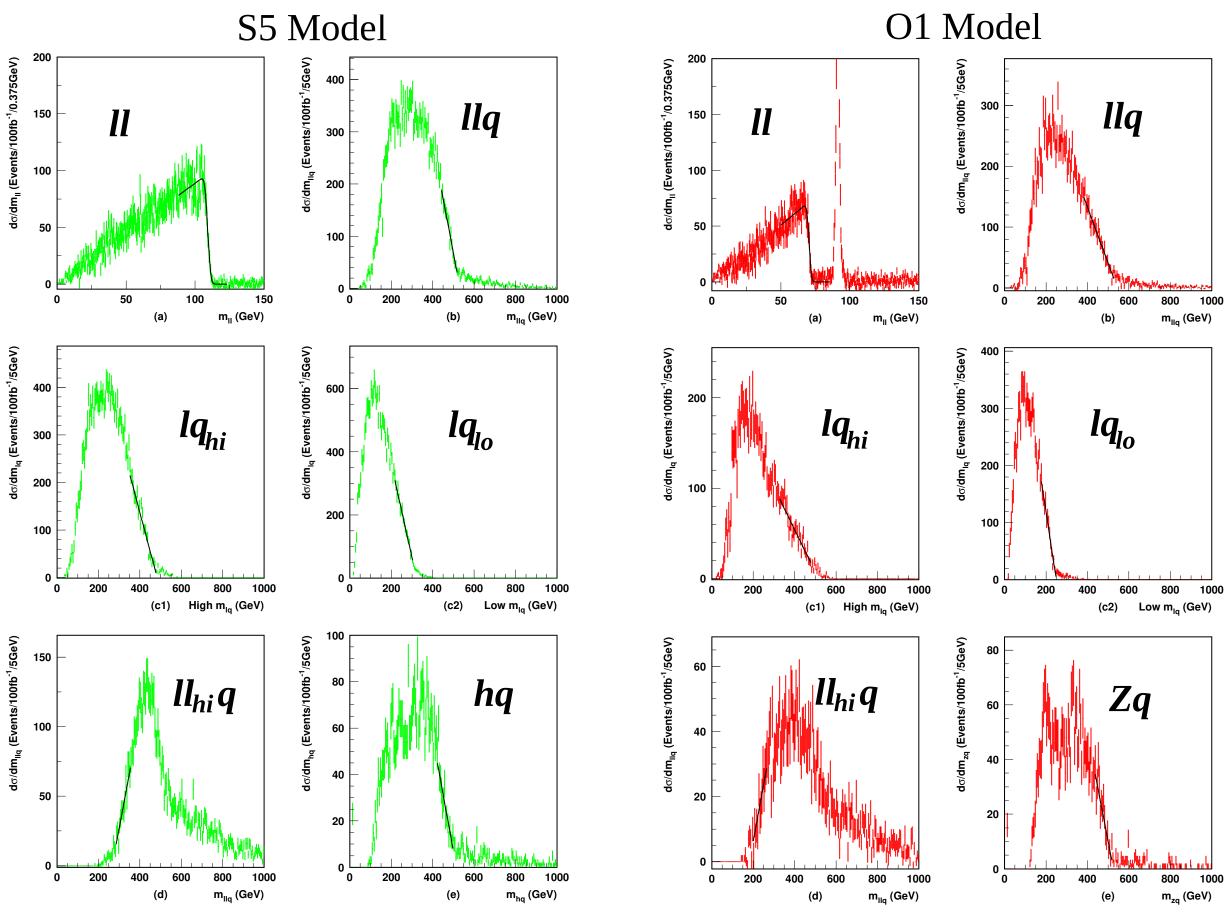
- String-motivated models suggest non-universal SUSY breaking. "Optimised" model of Casas, Ibarra & Muñoz (O1 model, hep-ph/9810266) is similar to mSUGRA model S5 except sleptons are heavier.



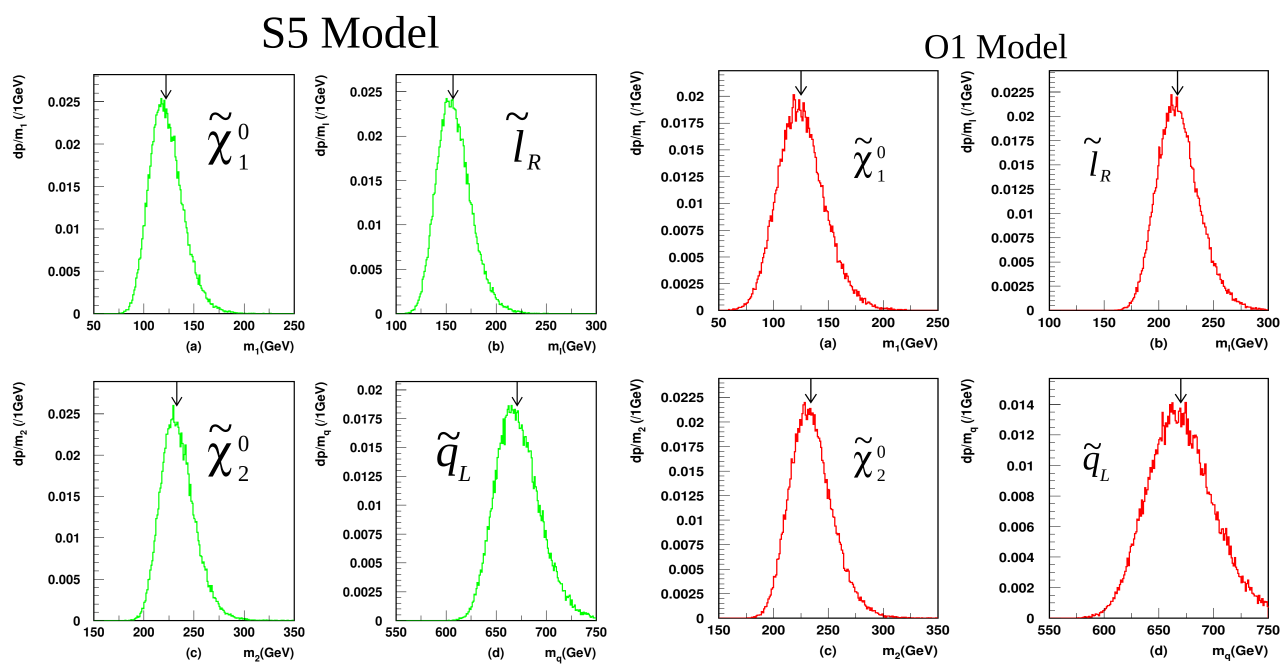
- SUSY masses are deduced from spectral "edges" due to decay chains







- Masses are reconstructed by fitting edge positions:



- N.B. Peaks are distributions over experiments, each with $\int \mathcal{L}\, dt = 100$ fb^{-1} $\sim$ 1 year at high luminosity.

- Useful new variable M_{T2} for finding processes like

$$pp \to \tilde{l}_R^+ \tilde{l}_R^- X \;, \qquad \tilde{l}_R^+ \tilde{l}_R^- \to l^+ \tilde{\chi}_1^0 l^- \tilde{\chi}_1^0 \;:$$

CG Lester & DJ Summers, hep-ph/9906349

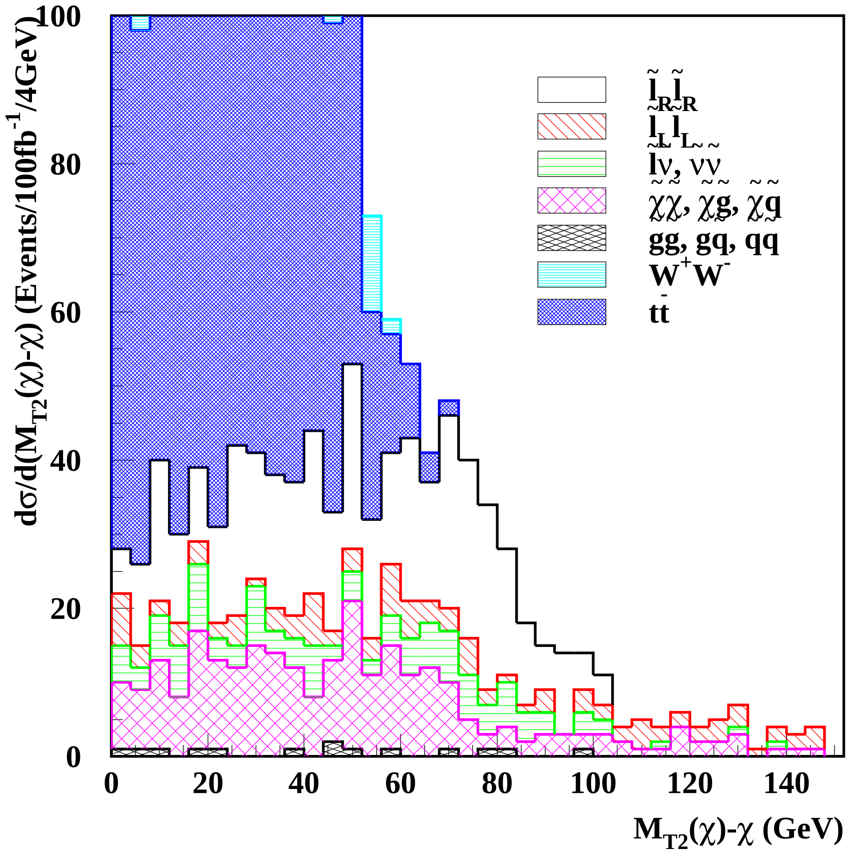
$$M_{T2}^2(\chi) \equiv \min_{\not{\mathbf{p}}_1 + \not{\mathbf{p}}_2 = \not{\mathbf{p}}_T} \left[\max \left\{ m_T^2(\mathbf{p}_T^{l^+}, \not{\mathbf{p}}_1, \chi), m_T^2(\mathbf{p}_T^{l^-}, \not{\mathbf{p}}_2, \chi) \right\} \right]$$

where

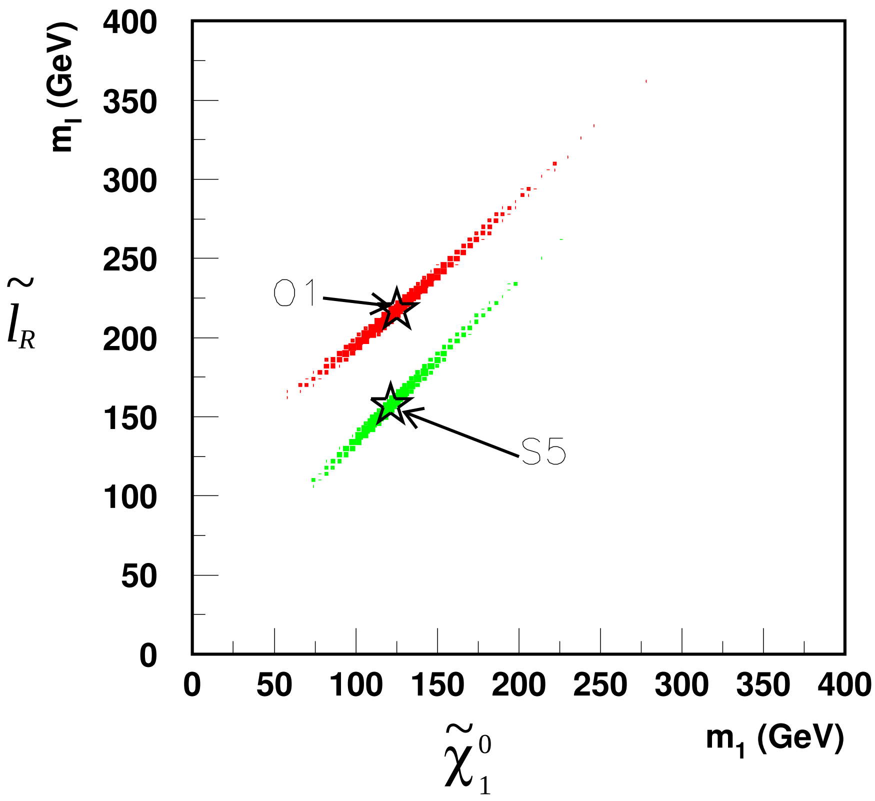
$$m_T^2(\mathbf{p}_T^l, \not{\mathbf{p}}, \chi) \equiv m_l^2 + \chi^2 + 2(E_T^l E_T^\chi - \mathbf{p}_T^l \cdot \not{\mathbf{p}})$$

$$E_T^l = \sqrt{\mathbf{p}_T^l + m_l^2} \qquad \text{and} \qquad E_T^\chi = \sqrt{\not{\mathbf{p}}^2 + \chi^2}$$

O1 Model



- Models are distinguished even though mass distributions are broad.

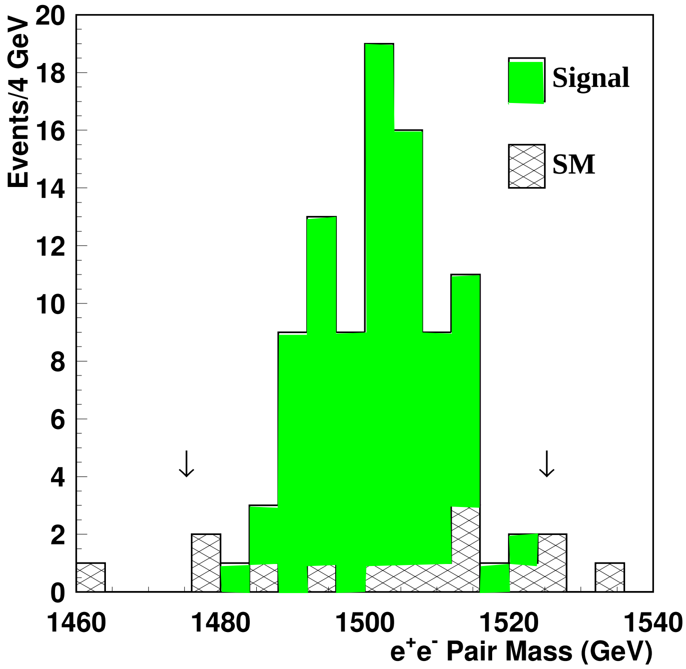


Searching for Graviton Resonances

BC Allanach, K Odagiri, MA Parker & BRW, hep-ph/0006114

- In non-factorisable geometry (Randall-Sundrum) models there may be narrow graviton excitations G with TeV-scale masses.

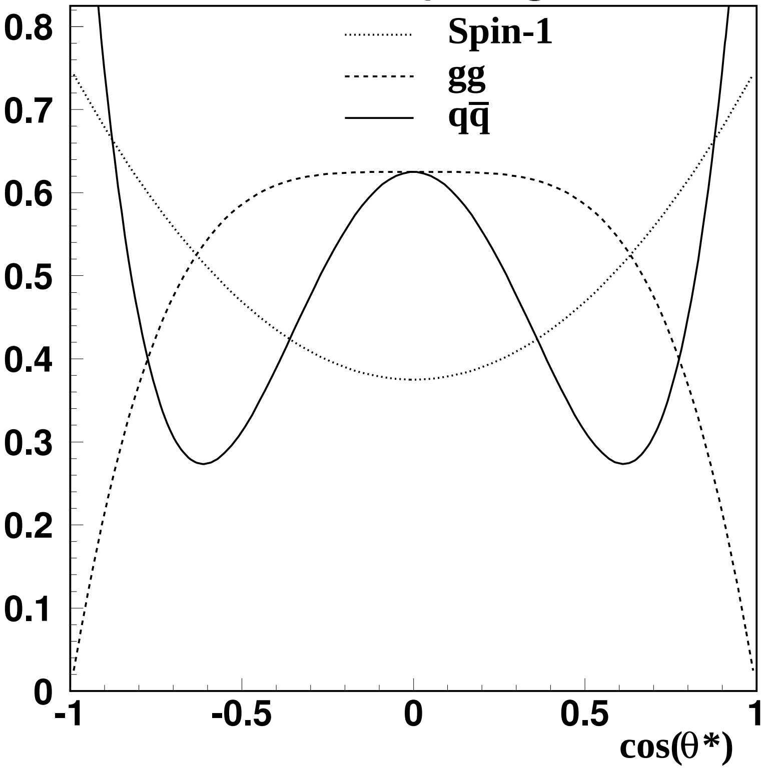
- What to look for?
  - SM interaction strength $\Rightarrow$ easily produced above energy threshold but decays promptly to SM particles
  - Interacts directly with energy-momentum $\Rightarrow$ decays "democratically" to all types of particles
  - Electrons easiest to measure $\Rightarrow$ look for resonance peak in electron-positron pairs:



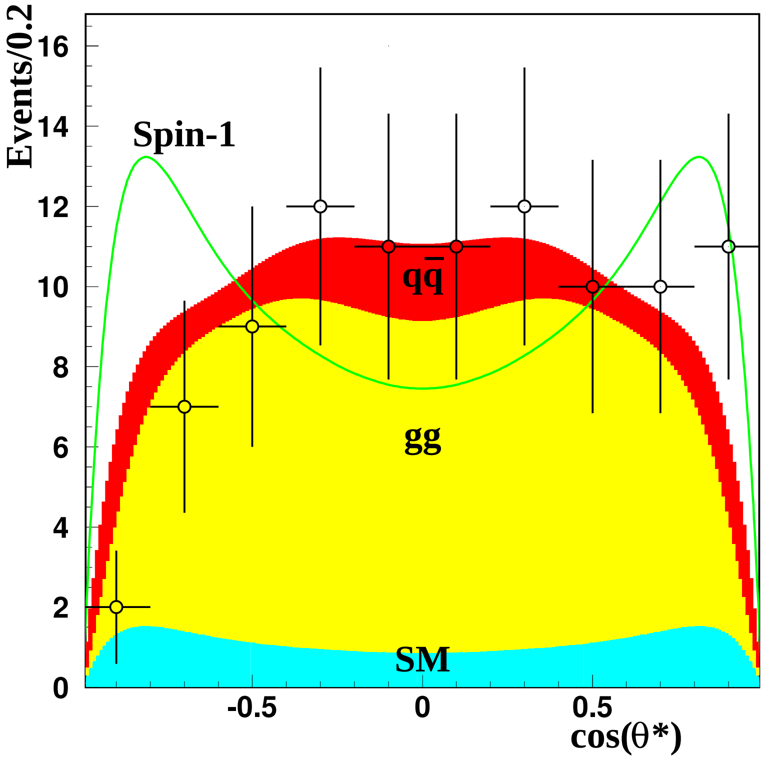
  - Hatched boxes show background from SM processes
  - Width of peak due to detector resolution ($\Gamma_G \sim$ GeV)

Identifying a Graviton Resonance

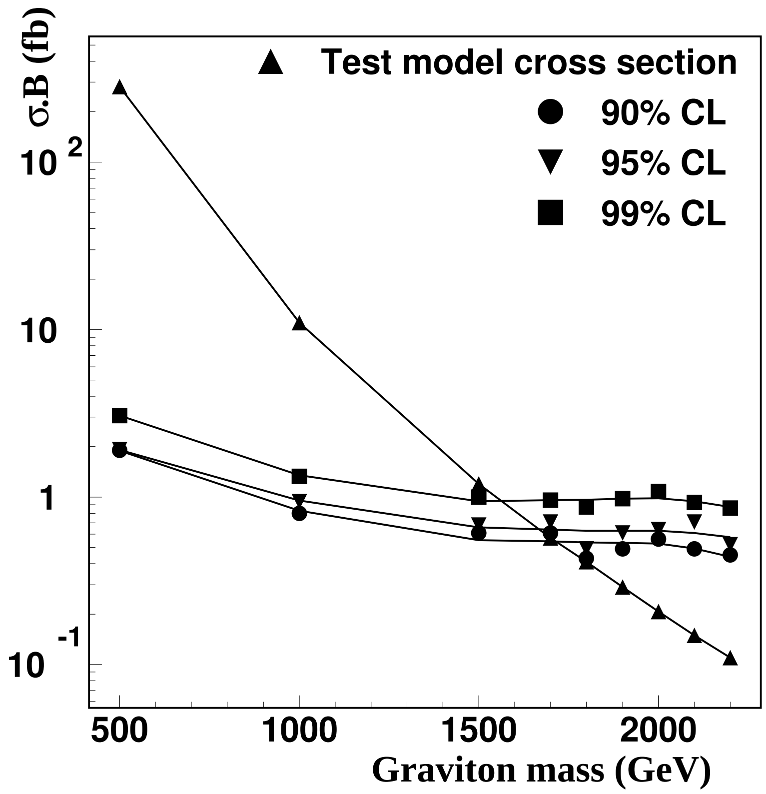
- How would we know it's not e.g. a gauge boson (Z')?
  - "Democratic" interactions ⇒ other decays, e.g. $\gamma\gamma$
  - Gravitons have spin 2 ⇒ decay angular distribution:



  - After full simulation (including ATLAS detector):



- Can be identified as spin-2 up to > 1500 GeV:



- Other modes can be checked for universality: $\mu^+\mu^-$, $\gamma\gamma$, jet-jet, W^+W^-, . . .

Black Hole Production

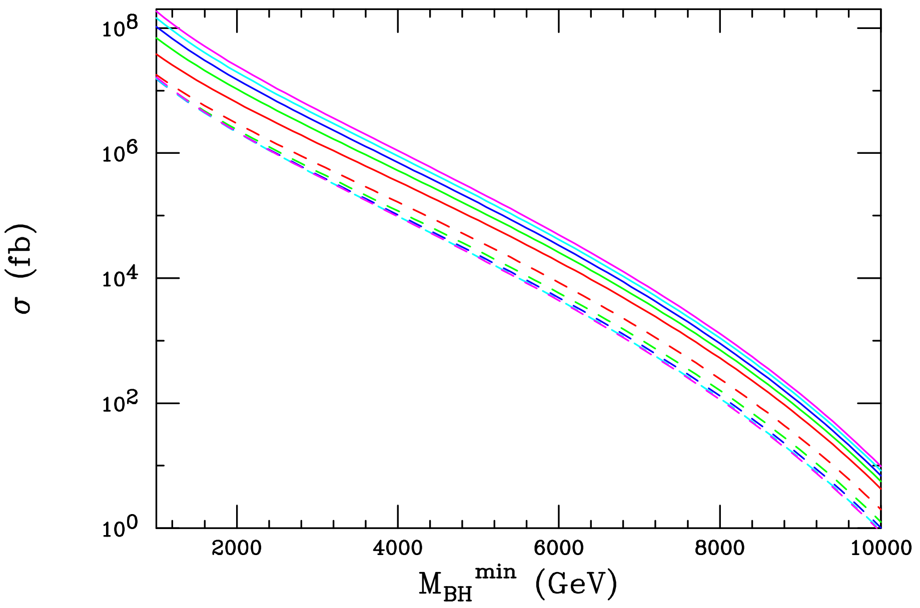
CM Harris, P Richardson, in preparation

- Black hole radius (assuming $r_h \ll R$)

$$V(r_h) = \left(\frac{\hbar}{M_0 c}\right)^n \frac{m_h^2}{M_0^2} \frac{\hbar c}{r_h^{n+1}} \sim m_h c^2$$

$$\Rightarrow \quad r_h \sim \frac{\hbar}{M_0 c}\left(\frac{m_h}{M_0}\right)^{\frac{1}{n+1}}$$

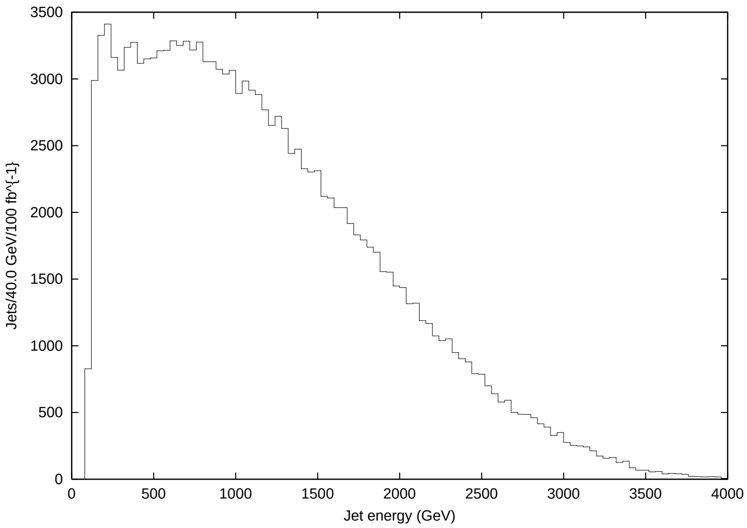
- Classical approximation for cross section (somewhat controversial!) $\sigma_{\rm BH} \sim \pi r_h^2$ implies copious production (for $n = 2 \ldots 6$ extra dimensions):



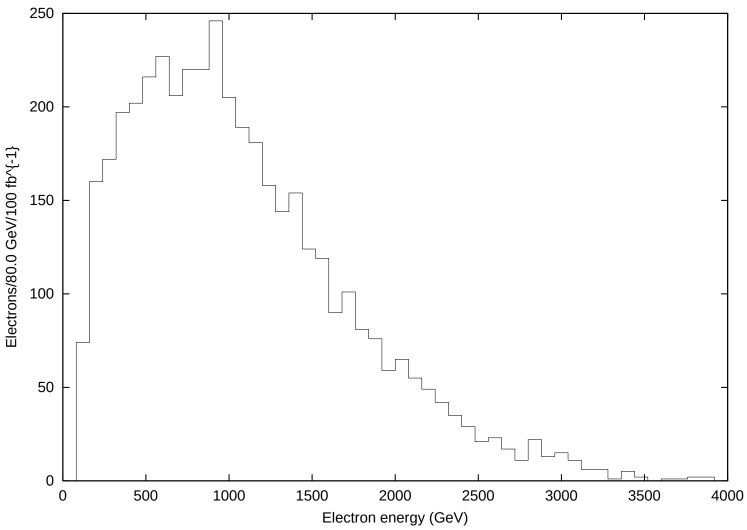
- Decay (safely!) by Hawking radiation
  - $T_H = (n+1)/4\pi r_h$
  - Measure T_H and hence n from spectrum?

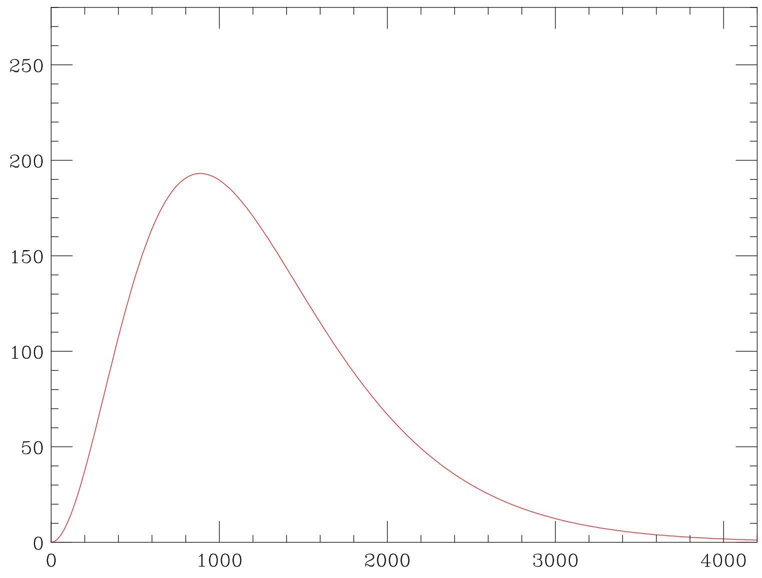
- Example: $n = 6$ extra dimensions, Planck mass $M_0 = 2.0$ TeV (Dimopoulos-Landsberg definition), black hole mass $m_h = 7.0 - 7.5$ TeV
  - Hawking temperature $T_H \sim 400$ GeV
  - Particle multiplicity $\langle N \rangle \sim m_h/2T_H \sim 9$.

- Spectrum of all jets:



- Spectrum of isolated electrons:

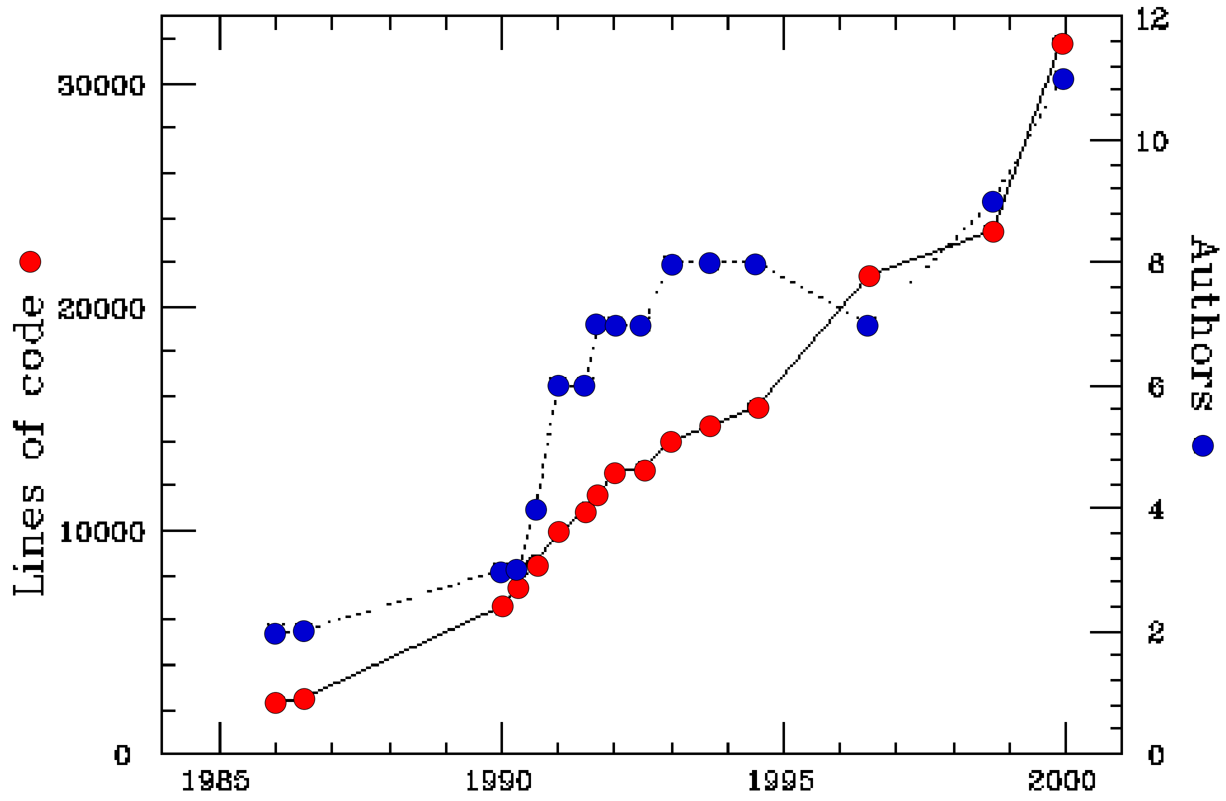




- Electron spectrum deviates from ideal black body
  - Isolation cut?
  - Recoil effects?
  - Work in progress. . .

Future Plans

- Program has expanded $\times 20$ over 15 years



- Software maintenance and development becoming impossible (and students don't learn Fortran . . .)

- New Object Oriented Program HERWIG++ under construction

  - Standard class structure and interfaces (CLHEP, PYTHIA7, . . .)
  - New physics (multijets, SUSY showering, . . .)

S Gieseke, A Ribon, M Seymour, P Stephens & BRW, 2003?

Conclusions

- HERWIG contains the right perturbative physics to describe wide range of data from LEP and Tevatron (also HERA):
  - Angular ordered parton showers
  - Matrix element corrections
  - Full spin correlations

- Non-perturbative physics needs improvements:
  - Heavy flavour hadronization
  - Baryon production
  - Underlying event

- New physics studies
  - Distinguishing SUSY models difficult but possible
    - LC would help!
  - Extra dimensions: graviton excitations easy
    - Black holes under study

- Future: HERWIG++